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Study on Power Train of Two Axles Four Wheel Drive Electric Vehicle

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Abstract

This paper is focused on design of a power train for two-axle four-wheel-drive (4WD) electric vehicle (EV). The purpose is to improve the energy efficiency, driving stability for an Utility Vehicle (UV) that is original equipped with a 500cc internal combustion engine. The designed power train is consisted of two 5kw brushless DC motors (BLDC) with the associated motor drivers, automatic manual transmission (AMT), AMT controllers, and 288V16AH Lithium-ion battery pack. The works include power train specification design, mechanism and controller design for the clutchless AMT, optimal transmissions gear-shifting strategy design, and finally, power split strategy design for the 4WD in terms of wheel slip ratio control. To guarantee AMT gear-shifting quality, the gear-shifting maps was applied in gear change process. The power split strategy design for the 4WD EV was based on sliding mode algorithm, it was shown through numerical simulation that slip ratio on each wheel can be controlled within an optimal value in ECE40 drive pattern.

Keywords: Electric vehicle, automatic manual transmission

1. Introduction

In order to reduce pollution and its impact on the environment, significant effort has been devoted to the research and development of eco-friendly electric vehicles. Due to developments in power electronics technologies and electric components, pure electric vehicle have attracted worldwide attention and various types of EVs have been developed as results [1]–[3]. These EV drive systems can be classified according to the wheel driven by the motor, i.e., front or rear wheels driven by only one motor, front or rear wheels driven by two motors, and four wheels driven by in-wheel motors.

To improve efficiency of an electric driving system meanwhile to meet the requirements of vehicle drivability, the driving motor of the pure electric vehicle is usually provided with a decelerator or a transmission device. When constructing the EV, it is unreasonable to use an AT or continuous variable transmission (CVT) because an AT has considerable power losses and, currently, a CVT can only be applied for a small-sized passenger car [4]. The AMT can easily be implemented using a conventional multispeed manual transmission and pneumatic/ hydraulic or electric actuators to operate the shift levers. Hence, it can be tendency that AMT will be adopted in EV.

Conventional AMT for vehicles powered by internal combustion engine (ICE) requires an electronic controlled clutch to separate and engage engine power for gear change smoothly, because of high inertia

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of the ICE. This complicates the system and thus with high cost. In this study, an AMT design without the use of the clutch for electric vehicle (EV) is designed.

In transmission control, shift quality is one of the most significant considerations [5]. Torque hole and shifting time determine the shift quality. Torque hole happens when the drive shaft gear moves toward target gear and the transmission gear is unengaged. The torque hole deteriorates the driving comfort of the vehicle during gear shifting. Hence, the dual AMT of front-and-rear-axle-independent-drive type EV is designed to accomplish the gear shifting sequentially for improving the shift quality. Based on the motor drive system characteristics and the overall requirements of the vehicle, the feasibility and optimization as well as control strategy of applying AMT without clutch to electric vehicle drive trains are presented.

In EV with multiple power sources, the main challenge is to control multi-power sources efficiently. There are ongoing researches on multi-power control algorithms. These control algorithms, proposed in the literature, may be classified into three categories depending on the control methodology used as rule based control, global optimal control and local optimization approaches [6]. The main problem in power control applications is to find the adequate torque split between multi-power sources to minimize energy usage or emissions while the vehicle is requesting power with different speed characteristics. In this study, a power split strategy based on sliding mode algorithm is proposed for the two-axle 4WD EV. Performance of the control strategy is evaluated using MATLAB simulations, and it is proved that the structure of control method can prevent wheels slippage on low friction coefficient road.

2. 4WD EV drive systems configuration

The front-and-rear-axle-independent-drive type of 4WD vehicle by adopting separate motors at the front and rear axles provide many advantages. First, the EV has a securer structure to avoid unexpended sudden stops, even if the front or rear drive systems fail. Second, the EV have good drivability to efficiently drive the front and rear wheels, even in heavy traffic, and to allow the EV to quickly accelerate and to avoid power interrupt while gear shifting. Third, the EV possesses the ability to improve steering ability and stability on bad roads, such as wet, frozen, and snowy roads. The proposed hybrid concept is a two-axle 4WD electric vehicle, wherein the front and rear axle are excited by electric motors independently as illustrated in Fig. 1. The rotor shaft of Brushless DC (BLDC) motor is linked with automatic manual transmission (AMT), and the driving torque generated from the motor is transmitted to the wheel side through MT gearbox. The vehicle control unit (VCU) can independently operate front- and rear-axle drive system.

The hardware of power train system mainly consists of a 5KW BLDC, gear change mechanism, a MT gearbox, and an AMT controller, as shown in Fig. 1. The BLDC motor is the main power source for driving the vehicle. The AMT controller is composed of electric control unit (ECU), sensors and the actuators of automatic shift. The gear change mechanism is actuated by two DC motors. The parameters for the AMT electric control mainly consists of the rotation speed of the BLDC motor and input and output shafts of the MT gearbox, driver's throttle opening as well as shift lever signal, and positions of the gear change motors. By controlling motor speed and torque responsively and accurately, the speed between driving motor and output shaft of gears-train will be synchronized for smooth gear engagement. Thus the clutch apparatus is not required anymore.

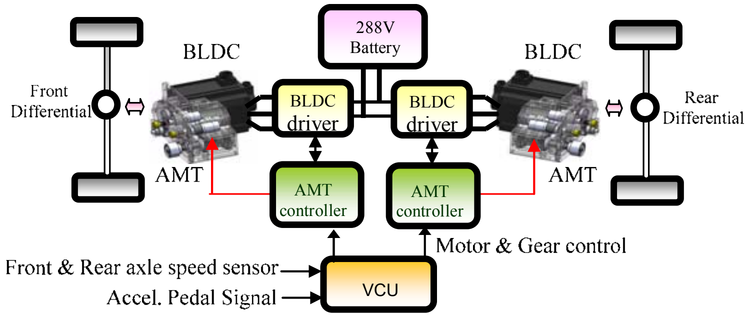

Fig. 1 Two-axle 4WD EV power train structure

3. Vehicle modeling

The vehicle dynamics must be described using a mathematical model to develop an efficient power split control strategy system for the proposed EV drive system. Thus, the modeling derivation of the entire mechanical system has been indicated in following.

3.1. Tire Dynamics

The longitudinal tire force F_{xi} as a function of longitudinal slip ratio is given by

$$F_{xi} = \mu_i(\lambda_i)F_{zi} \tag{1}$$

where the subscript i denotes the variables associated with the front or rear wheels, F_z is the vertical tire load, and μ is the road friction coefficient, which is a function of the tire slip ratio λ and is modeled as a lookup table. The slip ratio λ can be expressed as

$$\lambda_i = \begin{cases} \dfrac{r_w\omega_i - v}{r_w\omega_i} \text{ (braking)} \\ \dfrac{r_w\omega_i - v}{v} \text{ (driving)} \end{cases} \tag{2}$$

where r_w is the wheel radius, v is the longitudinal vehicle speed, and ω is the rotational speed.

3.2. Longitudinal dynamics

The external forces acting on the vehicle in the longitudinal direction are the longitudinal tire, aerodynamic, rolling resistance forces. These forces are displayed graphically in Fig. 2. The proposed drive system is a two-axle 4WD electric vehicle, wherein the front and rear axle are excited by electric motors independently, so that the longitudinal dynamic can be simplified as two-axle vehicle model. Important considered parameters for vehicle dynamic include vertical tire load variation for front and rear wheels as well as longitudinal weight transfer caused by the acceleration or deceleration.

Vehicle motion in longitudinal can be expressed as follows:

$$\dot{v} = \frac{1}{m_t}(\mu_f F_{zf} + \mu_r F_{zr} - F_A - f_r F_{zr} - f_f F_{zf}) \quad , \quad F_A = 0.5 \times C_D A \rho v^2 \tag{3}$$

$$\dot{\omega}_f = \frac{1}{J_f}\left[T_f - F_{zf}\mu_f r_w\right] - \frac{1}{J_f}\beta_f\omega_f \quad , \quad \dot{\omega}_r = \frac{1}{J_r}\left[T_r - F_{zr}\mu_r r_w\right] - \frac{1}{J_r}\beta_r\omega_r \tag{4}$$

$$F_{zf} = \frac{m_t}{a+b}(gb - \dot{v}h_{CG}) - \frac{h_A}{a+b}F_A \quad , \quad F_{zr} = \frac{m_t}{a+b}(gb + \dot{v}h_{CG}) + \frac{h_A}{a+b}F_A \tag{5}$$

where a and b are the distance from center of gravity to front and rear axle respectively, J_f and J_r are the moment of inertia of the front and rear wheels, f_f and f_r are the rolling resistance coefficient, m_t is total mass of the vehicle, F_A is the aerodynamic force, ρ is the mass density of air, C_D is coefficient of aerodynamic resistance coefficient, A is a characteristic area of the vehicle, h_A is the height of the point if application of the aerodynamic resistance.

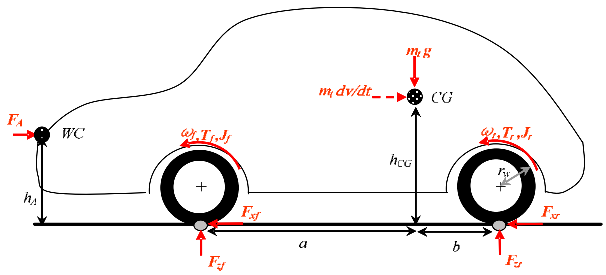

Fig. 2. The vehicle free body diagram

4. Torque distribution control

In general, the road conditions for the front wheels and rear wheels of a vehicle differ from each other. In order to accurately convert the driving force applied to each wheel on the front or rear end into propelling force (longitudinal force), it is necessary to ensure that the front and rear motors generate a torque that corresponds to the tire-road friction coefficient. In order to achieve this, a sliding mode control theorem, which controls the front and rear motor torque distribution ratio to prevent wheels slip, is applied to 4WD EV using the following procedures. Due to the slip ratio λ for wheels during acceleration is defined as Eq. (2), the speed difference between front and rear axle is calculated as slip ratio function

$$e = \omega_f - \omega_r = \frac{\lambda_f - \lambda_r}{(1-\lambda_f)(1-\lambda_r)} \tag{6}$$

The proposed torque distribution control is based on sliding mode control, and defined the torque distribution ratio as s_0 at present moment and $s = s_0 + \triangle s$ in the next time period.

When Eq. (4) is neglected the viscous friction term and supposed the same parameter, the equations can be re-expressed as :

$$\dot{\omega}_r = \frac{1}{J}((1-s)T_{req} - r_w \mu_r(\lambda_r) F_{zr}) \quad , \quad \dot{\omega}_f = \frac{1}{J}(sT_{req} - r_w \mu_f(\lambda_f) F_{zf}) \tag{7}$$

In order to satisfy global sliding mode condition, we define a sliding surface as $e = \omega_f - \omega_r$, then

$$\dot{e} = \dot{\omega}_f - \dot{\omega}_r = \frac{1}{J}[(2s-1)T_{req} - (\mu_f(\lambda_f)F_{zf} - \mu_r(\lambda_r)F_{zr})r_w] \tag{8}$$

The sliding mode control rule could be designed as:

$$s = s_0 - k_1 \mathrm{sign}(e) \tag{9}$$

where k_1 must satisfy the condition $0.5 > k_1 > k_{1\min}$ and $k_{1\min} = \left| \frac{(\mu_f(\lambda_f)F_{zf} - \mu_r(\lambda_r)F_{zr})r_w - (2s_0 - 1)T_{req}}{2T_{req}} \right|$

When the torque distribution ratio s is managed by Eq. (9), we can satisfy sliding condition $e\dot{e} < 0$, and the sliding surface $e = 0$ could be a stable invariant set.

5. Gear-shifting strategy

For various load conditions and vehicle speeds, the shift strategy determines the gear-shifting points so that the drive train can be operated with increased efficiency (the high efficient region of electric motor).

An AMT gear-shifting strategy is presented which is utilized to extract the up-shift and down-shift maps considering the motor speed, and the torque request requirements. This strategy avoids AMT gear-shifting over-frequently and motor operation at low speeds and it also considers the driver's torque request not to over-burden the motor. As shown in Fig. 3, the gear-shifting maps in which the gear positions are described according to the driver's throttle versus the vehicle speed are developed. The gear-shifting maps for driving mode are stored in the main controller memories.

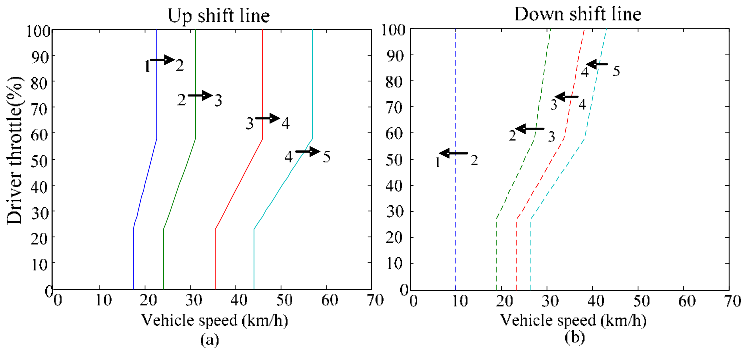

Fig. 3 Gear-shifting map (a) up-shift and (b) down-shift map

6. Verification of vehicle performance through simulations

Fig. 4 shows a block diagram of the torque distribution control based on sliding mode control method for the proposed EV drive system. This control strategy is possessed of wheel slip control by taking into account the speed difference between front and rear axle. In Fig. 4, ECE40 driving pattern is used as the vehicle velocity profile to be followed during the simulation. The driving model, i.e. a PID controller, is imitated professional driver's pedal accelerator and brake manipulation for following ECE40 driving mode. In the pedal evaluator, the required torque T_{req} is estimated according to driver's pedal loading. In accordance with the required torque of front and rear axle and current vehicle speed, the AMT controller can assign the required gear for independent axles. In slip ratio calculator, the torque split ratio (s) is calculated by according to the speed difference between front and rear axle. Finally, the torque distributor will distribute the reference torque command of front axle ($T_{mfref}= T_{req}*s/g_f$) and the reference torque command of rear axle ($T_{mrref}= T_{req}*(1-s)/g_r$).

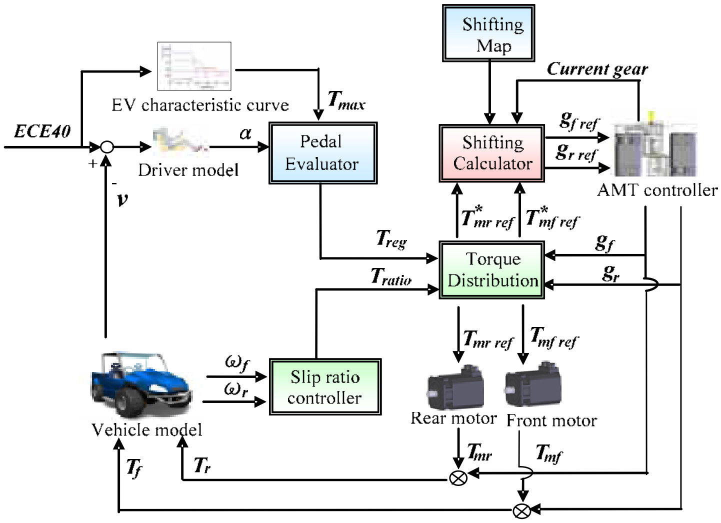

Fig. 4 Block diagram of the control strategy for the proposed EV drive system

Here, the running ECE40 performance of the vehicle is evaluated when the proposed control strategy is applied to the two axles 4WD EV. For comparing the effectiveness of the proposed torque distribution control method, Figs.5-7 show the simulation results for the two axles 4WD EV while the torque distribution ratio is fixed as 50%. Fig. 5(a) and 5(b) shows the distributing location of the front- and rear-wheel slippage respectively, sign as green asterisk, while running ECE40 driving pattern. As results, there is some occurrence of the slip phenomenon in front wheels.

Figs. 6 and 7 show the significant responses of front and rear wheels respectively. In Figs. 6(b) and 6(c), because of the weight transfer during acceleration period, the front tire-road friction is diminution resulted in the occurrence of slip phenomenon. In Fig. 7, due to the normal load of rear increase during acceleration, the rear wheel slippage is maintained below 0.1, which is smaller than the front wheel slippage.To evaluate the effectiveness of the proposed torque distribution control method, Figs.8-10 show the vehicle dynamic responses with proposed control strategy under the same driving condition. Fig. 9 and Fig.10 show the performance of torque distribution control for the front and rear wheels individually and the slip ratio of each wheel is effectively suppressed to optimal value below 0.1. Therefore, it is confirmed that the proposed control strategy allows 4WD EV to move stably and possessed of wheel slip control.

7. Conclusion

EV with independently driven front and rear wheels, which can simultaneously enhance drivability and safety, were designed. The EV drive systems were constituted so that these requirements are achieved more effectively. In addition, a torque distribution controller based on sliding mode control method for 4WD is developed. Wheel slip control is performed in coordination between the front and rear torque distribution. The effectiveness of the proposed control strategy is verified through simulations in low friction coefficient road condition.

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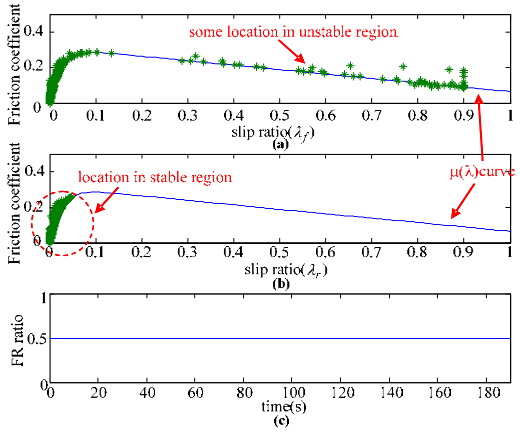

Fig. 5 Simulation results under torque distribution ratio fixed as 0.5 (unctrolled)
(a) distributing location of front wheel slippage
(b) distributing location of rear wheel slippage
(c) torque distribution ratio between front and rear axles

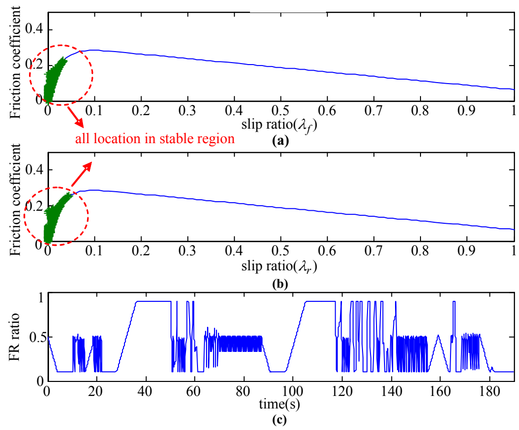

Fig. 8 Simulation results with the proposed control method
(a) distributing location of front wheel slippage
(b) distributing location of rear wheel slippage
(c) torque distribution ratio between front and rear axles

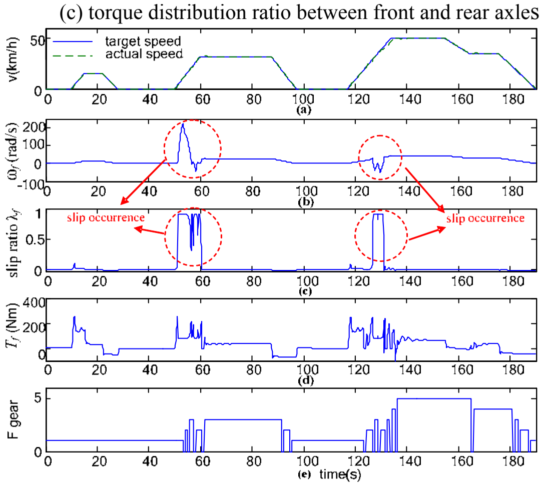

Fig. 6 Dynamic performance of front wheel under uncontrolled
(a) vehicle speed response (b) wheel speed (c) slip ratio
(d) front axle torque (e) AMT gear of front axle

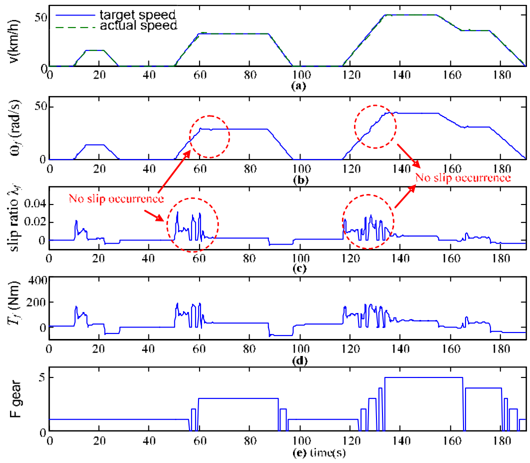

Fig. 9 Responses of front wheel under the proposed control method
(a) vehicle speed response (b) wheel speed (c) slip ratio
(d) front axle torque (e) AMT gear of front axle

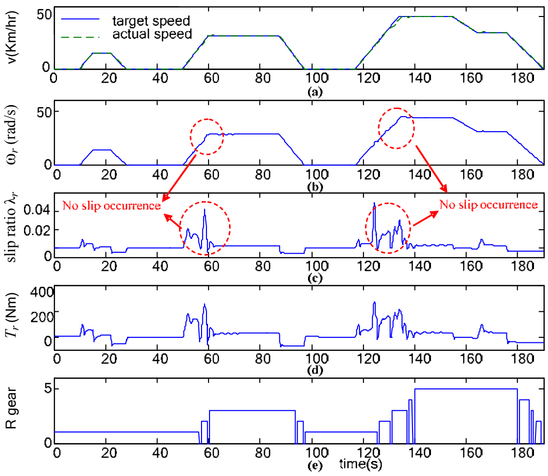

Fig. 7 Dynamic performance of rear wheel under uncontrolled (a) vehicle speed response (b) wheel speed (c) slip ratio (d) rear axle torque (e) AMT gear of rear axle

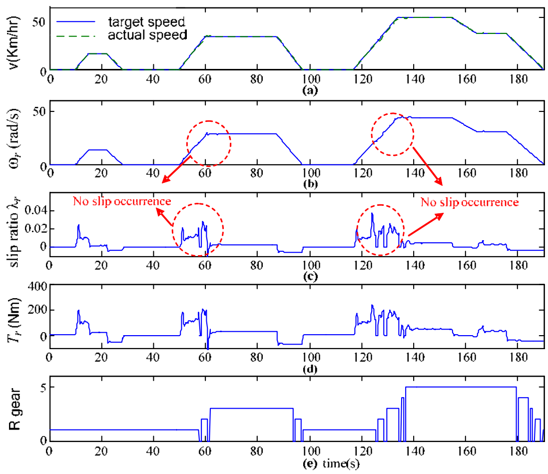

Fig. 10 Responses of rear wheel under the proposed control method (a) vehicle speed response (b) wheel speed (c) slip ratio (d) rear axle torque (e) AMT gear of rear axle